



## INFRARED SPECKLE INTERFEROMETRY WITH 2-D ARRAYS

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**Abstract**—We describe results from a program of speckle interferometry with two-dimensional infrared array detectors. Analysis of observations of  $\eta$  Carinae made with a  $58 \times 62$  InSb detector are discussed. The data have been analyzed with both the Labeyrie autocorrelation method, a deconvolution of shift-and-add data, and a phase restoration process. Development of a new camera based on a much lower noise HgCdTe detector will lead to a significant improvement in limiting magnitude for IR speckle interferometry.

### I. INTRODUCTION

Speckle interferometry is a technique to obtain spatial information on astronomical sources at spatial frequencies up to the true diffraction limit of a ground-based telescope in spite of atmospheric seeing limitations. The pioneering work of Labeyrie<sup>(1)</sup> in this field delineated the basic ideas of speckle interferometry. In principle, one obtains a sequence of short exposure images of an object as well as a nearby point source calibrator. The observed power spectrum of the object divided by that of the calibrator then provides an estimate of the true power spectrum of the object with the effects of seeing removed. In order to recover a true image of the object, rather than just its power spectrum (or autocorrelation in image space), various techniques have been developed for estimating the phase of the Fourier components of the image. For example the Knox-Thompson technique<sup>(2)</sup> is based on averaging the gradient of the phase which is much less affected by seeing than the actual phase. Similarly, the triple correlation bispectral technique<sup>(3)</sup> takes advantage of the phase constancy around a closed triangle in Fourier space, "phase closure".

In this paper we report on the results of speckle interferometry obtained with two dimensional infrared array detectors. These data have been obtained on several telescopes over the period 1988 to the present, though most of the work described in this paper is from one observing run. We discuss the instrumentation used, data acquisition techniques, and three methods of analyzing the data to estimate the image up to the full diffraction limit of the telescope. We also mention results from the first testing of a new, second generation infrared array detector for speckle interferometric observing.

### II. INSTRUMENTATION

Most of our work has been done with a  $58 \times 62$  pixel array manufactured by Santa Barbara Research Center specifically for IR astronomy. This InSb array is sensitive from 1 to  $5.5 \mu\text{m}$ , has a quantum efficiency,  $Q.E. > 50\%$ , and a read noise of about 400 electrons. The array was used with optics which provided a plate scale of  $\sim 0.05''/\text{pixel}$ . This system has been used on the McDonald Observatory 2.7-m telescope, the NASA 3.0-m IRTF, the University of Hawaii 2.2-m, and Anglo Australian Observatory 3.9-m telescopes. The observations discussed here were all obtained on the latter telescope with broadband filters at H ( $1.6 \mu\text{m}$ ), K ( $2.2 \mu\text{m}$ ), and L' ( $3.8 \mu\text{m}$ ). In addition to this system, we have recently developed a speckle camera based on a NICMOS 3

HgCdTe detector from Rockwell which has a  $256 \times 256$  pixel format and is sensitive from 1 to  $2.5 \mu\text{m}$  and has a read noise of order 30 electrons. This system has been used on one engineering run on the McDonald 2.7-m telescope in poor weather conditions: we mention preliminary results from this run.

### III. SPECKLE OBSERVING TECHNIQUES

The single most important factor in speckle observing is to obtain a good statistical average of the seeing. We typically took a sequence of 500–1000 short exposure images on the object of interest (100 ms integration time), and then a similar length set of images on a known reference point source, as close in angular distance as possible to the prime source. Interspersed with these observations were sequences on empty sky and on a “blank” position of the filter wheel in order to obtain flat field information and to characterize the limiting noise “floor” of the observations. Because of limitations in the data system, principally disk storage and backup times, the time between observations of the object and reference point source was typically several minutes. The total data obtained at each wavelength was of order a dozen such sets of 1000 images.

### IV. ANALYSIS TECHNIQUES

We have used three separate techniques to obtain information on the unusual IR star,  $\eta$  Carinae, which was observed at the Anglo Australian Telescope in 1989 May. For all three techniques the first step of the data reduction is correction for bad pixels. We found that a polynomial interpolation, averaged along four directions through each bad pixel, though time consuming, provided the best corrections.

The first technique is the original Labeyrie speckle process: the images are Fourier transformed (with a function applied to insure zero flux at the edges of each frame) and the modulus of the Fourier transform computed. The average modulus for a large number of frames of  $\eta$  Carinae is then found. After similar processing for the calibration object, the  $\eta$  Carinae modulus is divided by that for the calibrator. An inverse Fourier transform of this gives the autocorrelation of the source image. In principle, prior to this division, the noise “bias” is subtracted from both the object and calibrator moduli: that is, the modulus of the system noise is subtracted from each to insure that the division at high spatial frequencies is not affected by differing S/N in the two objects. In the case of these observations, the S/N was so high for both objects that this step produced no significant changes in the final results.

The second technique involves deconvolving a “shift-and-add” sum of the images. In this method, we recenter each image of the object, putting the brightest part in the center of the frame. In our case we used an algorithm which chose the brightest 4-pixel square as the center of the image. For images with only a few speckles, this technique can produce nearly diffraction limited images with no further processing. In our case, because a typical image still had tens of speckles, we used the “Clean” algorithm to deconvolve the  $\eta$  Carinae images using the shift-and-add images of the point source as the dirty beam. For “cleaning” the image was rebinned to a factor of four higher apparent resolution, i.e.  $248 \times 232$  pixels. It was found that beyond a few hundred iterations, no significant changes occurred in the derived image. The result of the Clean algorithm is an array of delta functions of various amplitudes representing the deconvolved map. In order to present this result in a meaningful way, we then reconvolved this array with a Gaussian beam having a FWHM comparable to that of the telescope’s diffraction limit.

The third technique for image reconstruction involves the Knox–Thompson algorithm for phase retrieval. In the original Labeyrie method, if a method can be found to determine the phases as well as the amplitudes of the individual Fourier components, then the true image, rather than its autocorrelation can be computed. Our technique entails computing the gradient of the phase at

each spatial frequency in both dimensions. For this method it is important to center each image in an average power sense before Fourier transforming. The computed phase gradients are then averaged over a large number of frames. The actual phase as a function of spatial frequency is then computed via a conjugate gradient solution which produces a least squares estimate of the phase consistent with the overconstrained gradients. \* Since the true Fourier transform of a real-valued function should be Hermitian, we then averaged the imaginary parts of the FFT at positive and negative frequencies and artificially "anti-symmetrized" the phase; this typically produced small changes to the final derived phase, but had the important effect of eliminating all imaginary components in the final image. One significant problem in true image reconstruction is that ringing in the final image can be easily produced, since small errors in the final phases and amplitudes readily lead to negative (unphysical) points in the image. In order to minimize this problem we apodize the Fourier amplitudes with a function which goes to zero at the highest spatial frequencies passed by the telescope. Therefore, the Fourier components with the largest uncertainties, those at the highest spatial frequencies, are highly attenuated in the final image.

We find that each of these three techniques produces results which are qualitatively similar to each other but with some noticeable differences in terms of the quantitative levels of faint emission around the central object and in the structure of the noise in the final image. These differences can be readily understood in terms of the differing limiting resolutions of the techniques and the limitations of the algorithms. Figure 1 compares the results of these techniques as applied to our data on  $\eta$  Carinae at  $2.2\ \mu\text{m}$ ; the upper two panels show the autocorrelation of the image as derived by the original Labeyrie technique (Autocorr Speckle) and, for direct comparison with the deconvolution technique, the autocorrelation of the deconvolved image. In the lower panel we show the actual image deconvolved from the shift-and-add data and the image derived from the

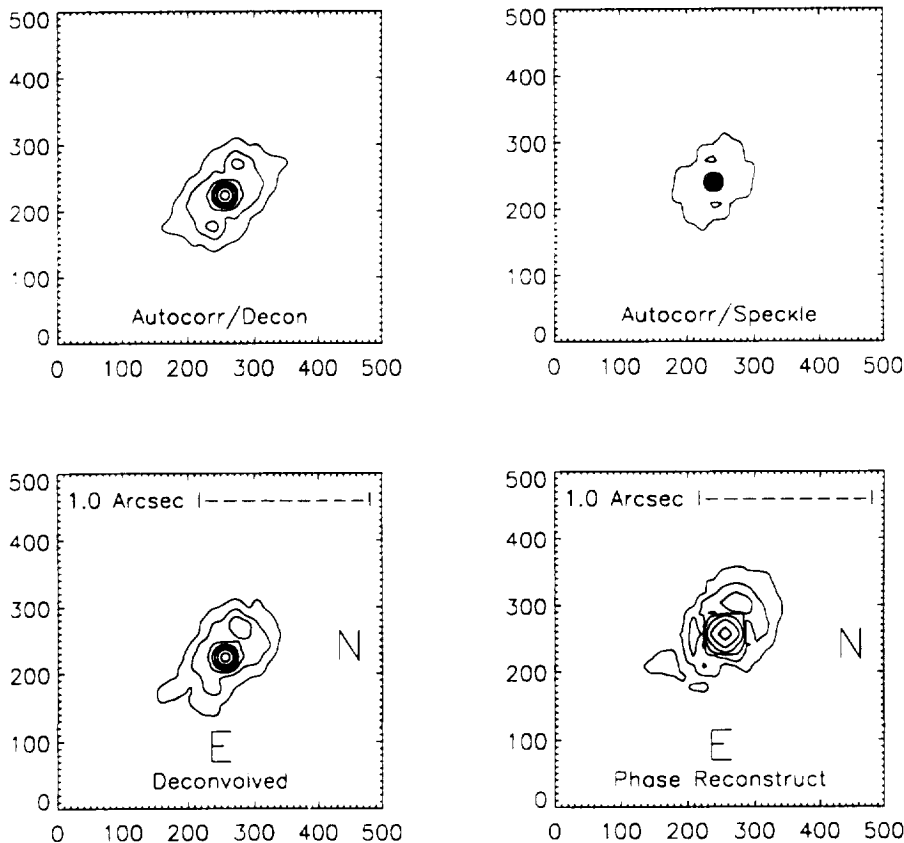


Fig. 1. Eta Carinae— $2.2\ \mu\text{m}$ .

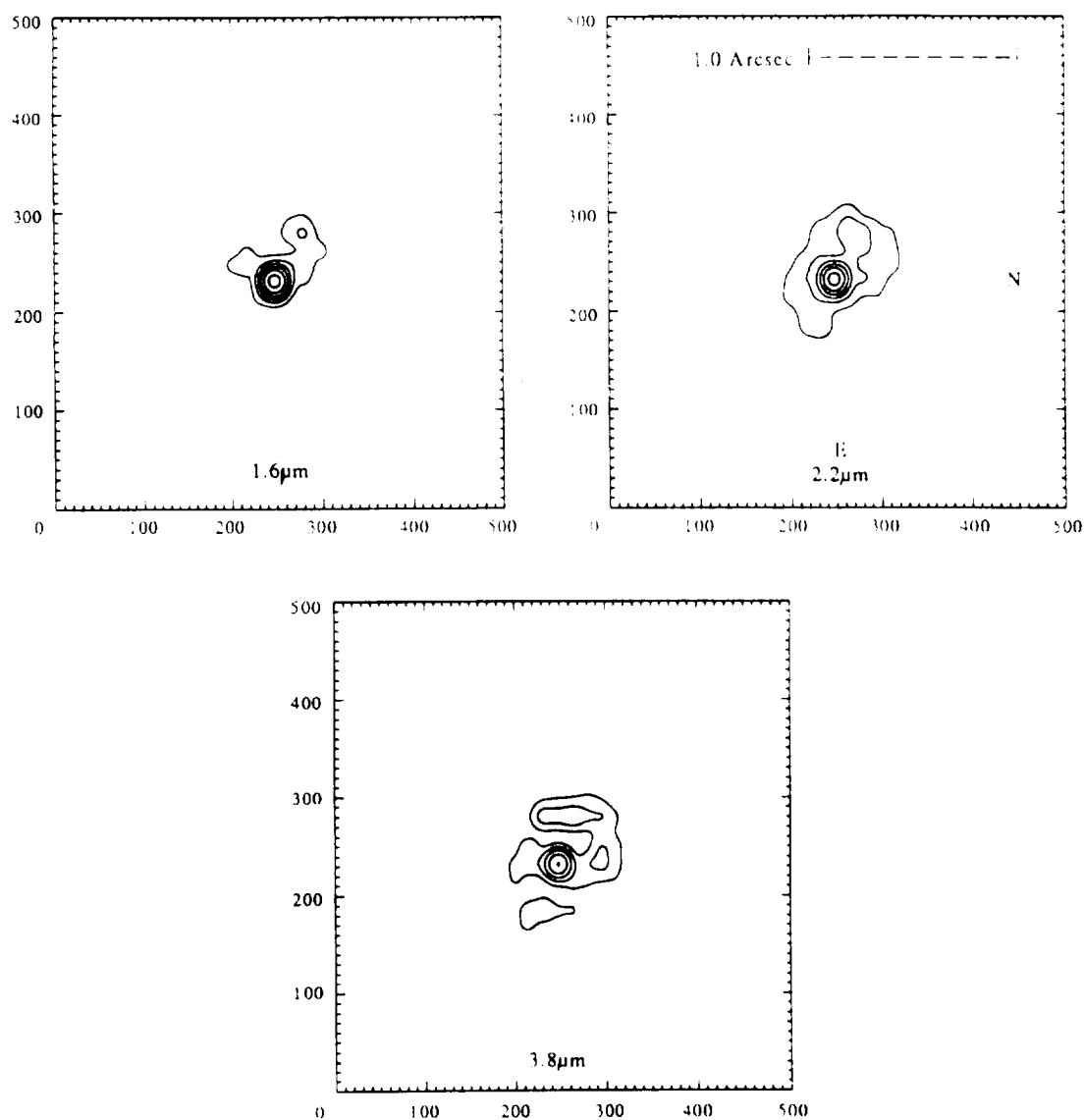


Fig. 2.

Knox-Thompson phase restoration process. Both of the image reconstructions show extended emission on an angular scale of order  $0.3\text{--}0.4''$  to the northwest of the central bright unresolved source and somewhat weaker emission to the southeast. The Knox-Thompson image, however, appears to exhibit some structure reminiscent of an Airy diffraction pattern; indeed, the radius of the dark and bright partially complete circular structures around the central source in that image are just the sizes expected at this wavelength from diffraction theory. Therefore, the derived image appears to be something of a convolution of the true image and a telescope diffraction pattern. This can be easily understood because of the nature of the reconstruction process; if there is some difference in the seeing between the average object data and the point source data, then this will lead to incomplete cancellation of the telescope point spread function in the final image. Because the Clean algorithm is inherently highly non-linear, this effect does not occur, though other types of noise effects certainly do exist.

Figure 2 shows the results of the deconvolution technique for all three wavelengths at which we observed  $\eta$  Carinae. As expected for any object in which a radial temperature gradient exists, the

size of the image clearly increases with wavelength. It is difficult to compare these images with those derived by other techniques and at other wavelengths because of differing angular resolutions and differing sensitivities to structure over a range of angular scales. It is likely significant, however, that the optical speckle image of  $\eta$  Car found by Hofmann and Weigelt<sup>5</sup> shows its only structure on a scale of 0.2–0.3'' to the northwest of the star, in the same direction and at roughly the same distance as our strongest emission. The 3.8  $\mu$ m image of Rigaut *et al.* (6) obtained with adaptive optics shows extended structure  $\sim 1''$  northeast and 0.7'' southeast of the central source; because of the smaller telescope and significantly longer wavelength, however, those data are not sensitive to structure at the 0.2'' spatial scale.

## V. NICMOS 3 DETECTOR RESULTS

We have obtained preliminary speckle interferometric data using one quadrant ( $128 \times 128$ ) of a NICMOS 3 array on the McDonald Observatory 2.7-m telescope. Because of clouds and very poor seeing, 3–4'', the data are not useful astronomically. We are, however, analyzing the data on point sources and double stars to compare with earlier data from the SBRC array. These analyses suggest that we can achieve the factor of 10 improvement in noise implied by the relative readout noises of the two systems. Further observations are expected in 1993 August.

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